Findings from NASA's 2015-2017 Electric Sail Investigations

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Abstract: Electric Sail (E-Sail) propulsion systems will enable scientific spacecraft to obtain velocities of up to 10 AU/year without expending any on-board propellant. The E-Sail propulsion is created from the interaction of a spacecraft's positively charged multi km length conductor/s with protons that are present in the naturally occurring hypersonic solar wind. The protons are deflected via natural electrostatic repulsion forces from the Debye sheath that is formed around a charged wire in space, and this deflection of protons creates thrust or propulsion in the opposite direction. It is envisioned that this E-Sail propulsion system can provide propulsion throughout the solar system and to the Heliosphere and beyond. The heliosphere is shown schematically in Figure 1. Consistent with the concept of a "sail," no propellant is needed as electrostatic repulsion interactions between the naturally occurring solar wind protons and a positively charge wire creates the propulsion.

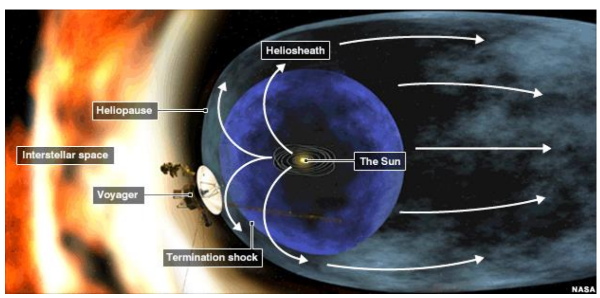

Figure 1. The Solar Systems Heliopause and Trajectories of the Voyagers

The basic principle on which the Electric Sail operates is the exchange of momentum between an "electric sail" and solar wind, which continually flows radially away from the sun at speeds ranging from 300 to 700 km/s. The "sail" consists of an array of long, charged wires which extend radially outward 10 to 30 km from a slowly rotating spacecraft (see Figure 2). Momentum is transferred from the solar wind to the array through the deflection of the positively charged solar wind protons by a high voltage potential applied to the wires.

The thrust generated by an E-Sail is proportional to the area of the sail, which is given by the product of the total length of the wires and the effective wire diameter. The wire is approximately 0.1 mm in diameter. However, the effective diameter is determined by the distance the applied electric potential penetrates into space around the wire (on the order of 10 m at 1 AU). As a result, the effective area over which protons are repelled is proportional to the size of the region of electric potential, or the plasma sheath region, surround the wires of the array.

A large sheath is, therefore, beneficial to the generation of thrust. However, this benefit must be balanced with the additional fact that electron collection is proportional to sheath size. Electrons collected by the wire array must be injected back into the solar wind in order to maintain the potential on the wires—which requires power. The primary power requirement for E-Sail operation is, therefore, also proportional to sheath size.

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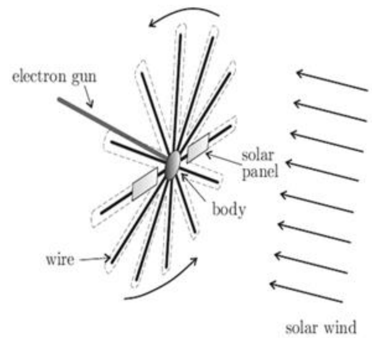

Figure 2. An Electric Sail obtains thrust by reflecting solar wind protons.

Size of the sheath is determined by the applied potential and how effectively the charged particles of the solar wind shield the electric potential. This shielding effect is proportional to electron density, so that as the solar wind density decreases with distance from the Sun as $1/R^2$, the shielding effect weakens and the sheath grows proportionately. This increases the effective area of the sail and partially compensates for the $1/R^2$ decrease in solar wind proton density (and, therefore, the force per unit area). As a result, the thrust produced by an E-Sail only decreases as $1/R^{7/6}$ with distance from the Sun while solar sail thrust decreases as $1/R^2$ thus providing a distinct advantage for the E-Sail. Whereas a solar sail mission stops accelerating at distances > 5AU the E-Sail missions will continue to accelerate the spacecraft to distances of ~15 AU

The TRL of Electric Sail systems is admittedly low – but this is only at the full system level. The subsystems required for an Electric Sail system to operate have almost all been demonstrated in space. What is lacking is a system-level, integrated demonstration.

The MSFC HERTS team over the past two years have conducted/completed experiment plasma physics within the one of the Space Effects plasma chambers at the MSFC. The experimental data obtained has been used to benchmark a Particle In Cell (PIC) electric sail spacecraft model that the University of Huntsville (UAH) has developed as a team member to determine the effectiveness of E-Sail propulsion systems. The outputs of this PIC model when coupled to various mission designs (out of the ecliptic plane, deep space, or NEA missions, etc.) performed by the JPL provide the various mission capture opportunities this revolutionary propulsion system will enable. For instance, this propulsion technology will enable trips to Pluto in ~ 5 to 6 years, Jupiter flybys in 24 to 30 months, and trips to the Heliopause region of the solar system in 10 to 12 years versus the >35 years it took the Voyager spacecraft.

An identification of the missions captured by this propulsion capability will be one of the highlights of this paper. In addition, recent work focused on a 2021-2023 E-Sail Technology Development Mission DM illustrates that a 12U spacecraft could get 45 degrees out of the solar system ecliptic plane within 3 years. Much of the teams work has been in the areas of tether material investigations and the trades performed in determining the best conductor tether to use in a TDM mission will also be documented and showcased in this paper.

Also, investigations of: Off –The-Shelf (OTS) electron guns that could be used in a TDM spacecraft design to electron guns for an all up Heliophysics mission have been performed and those systems that are OTS or easily modified to be integrated into near term missions have been identified in this paper.

And lastly a detained conceptual 12-U CubeSat spacecraft designed to perform a 2021-2023 TDM for E-Sails is documented in this paper.